INTERACTION MATRIX FOR PLANNING UNDERGROUND AMMUNITION STORAGE FACILITIES

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ABSTRACT: A systematic approach to planning underground ammunition storage based on an interaction matrix is presented. The interaction matrix is essentially a collection of the most important parameters with all possible interactions among them. Depending on the objectives of planning and design, several levels of the interaction matrix can be designed with the highest level having the least details, and the lowest level being complete with all relevant parameters included, which can be used for final planning and design. The advantages of the interaction matrix is that it gives you an overall picture at varying degrees of details. One parameter can not be changed without knowing its effects on the rest of the system. It also allows one to gather all relevant factors and mechanisms in a coherent structure. In this paper the basic structure of the interaction matrix is presented. Practical examples are then used to demonstrate the use of this system.

1. INTRODUCTION

The design of underground ammunition storage facilities is a very complex systems engineering. It involves many specialized areas such as rock engineering, ammo safety, and fortification design, each of which is again a complex subject. In countries like Singapore, the scarcity of land further complicates the problem; almost all constructions must minimize land use, and this also applies to underground ammunition storage, although it already uses much less land than surface storage.

As in most engineering design, the traditional approach begins with a definition of the user requirements. This requires that the user knows exactly what he wants in the design. Once the user requirements are defined, the designer identifies the constraints, including the available resources and the regulations, among others. The designer then undertakes the design to meet the user requirements within the constraints given to him. Some optimization may be possible if the designer is experienced and the systems behavior is well understood (although probably not from a systems point of view). This process is depicted in Figure 1.

However, when the requirements cannot be clearly defined, and when the regulations (design codes) are not sufficient, the traditional sequential approach will not work if one is to design a facility in the most economical and efficient way. For instance, the user may be reluctant to specify certain requirements because he is not sure of all the technologies available and wants to know how his requirements will affect the design of his final facility. The consultant, on the other hand, will have difficulty proceeding with any work because he insists that "you have not told me what you want!".

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This example illustrates the difficulty in evaluating a system as complex as underground ammunition storage. The number of parameters in planning and designing for such a complex system is so large that only a systematic approach can ensure the most efficient solution.

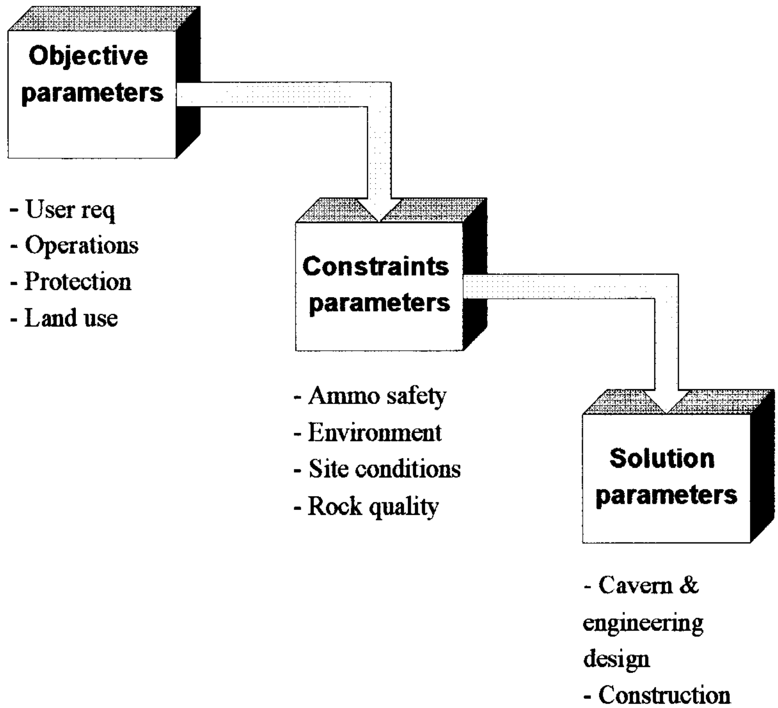

Figure 1. Sequential Approach to Engineering Design

2. INTERACTION MATRIX

2.1 The Concept of Interaction Matrix

The concept of the interaction matrix was originally introduced by Hudson[1] for representing the total system behavior of the rock engineering system. This concept is shown in Figure 2. As shown in Figure 2, the primary parameters are placed along the diagonal. In a clockwise fashion, the influence of Parameter A on Parameter B is shown in the box vertically above the box containing Parameter B while the influence of Parameter B on Parameter A is shown in the box vertically below the box containing Parameter A.

It is possible that Parameter B does not have any significant effect on Parameter A although there is an important effect of Parameter A on Parameter B. If this is indeed the case, we have already fulfilled our purpose, and in evaluating the system behavior, we can confidently ignore this relationship.

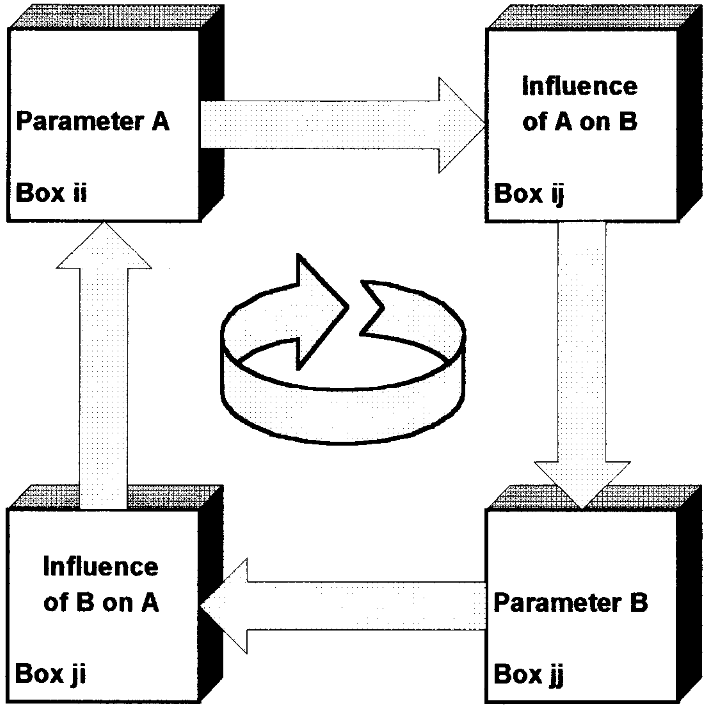

Figure 2. Concept of the Interaction Matrix (after Hudson[1])

In an interaction matrix, it is possible to have varying levels of interaction. For the purpose of our discussions, we classify them into three types of interactions:

a. Interaction between groups;
b. Interaction between parameters of different groups; and
c. Interaction between parameters of one group.

In our example, the two group parameters could be ammo safety and overall environment. Overburden requirement and out-loading time would be two parameters from the ammo safety group and user requirement group. And cavern dimensions and depth of cavern would be two parameters from the same group of cavern engineering.

2.2 Interaction between Groups

If we classify all system parameters into a number of groups, it is possible to have interaction between groups (Figure 3). In this case, each group would be the primary parameter. As shown in Figure 3, and in subsequent discussions, this interaction is in fact what will be defined as top level matrix. The example is used to show how ammo safety and the overall environment influence each other. For top level planning, this level of details is probably sufficient.

2.3 Interaction between Parameters of Different Groups

Interaction between parameters of different groups is most likely when the overall system is being examined in more detail (Figure 4).

Ammo safety	Land sterilization limits development
Housing distribution will affect direction of venting tunnel	Overall Environment

Figure 3. Interaction between groups

Overburden Req for non-responding magazine	Thick overburden means longer access tunnels.
Fast out loading time may limit rock cover	Out loading time: processing & traveling

Figure 4. Interaction between parameters of two groups

In view of the possible ground shock effects and the need to minimize land sterilization, overburden requirements for an underground can be classified into the following three categories:

a. Overburden for negligible debris within the ground shock IBD
b. Overburden for limited surface use
c. Overburden for "unlimited" surface use.

Obviously, the overburden requirement increases from a to c. Based on prevailing current codes and recommendations from Jenssen[2] these values are 1.0 and $2.5Q^{1/3}$ for a and b, respectively. For category c, when the depth is sufficient, there should be no restriction on use of the land above.

The choice of the overburden category will have a significant impact on the out-loading time and mode if a fixed out-loading time is required. For example, a reduction in overburden requirement will reduce the total length of a single access ramp by:

$$\boxed{\Delta L = \frac{\Delta H}{\sin\alpha}}$$

where α is the average gradient of the access ramp..

Larger overburden means smaller land sterilization due to ground shock. However, if the overburden requirement cannot meet the operational requirements of the out loading time, a

combination of horizontal tunnel and vertical shaft may be required as the primary mode of out loading. This change in turn will be reflected in the design, especially in the M&E requirement.

Once these interactions are established, it becomes much easier to evaluate how the overburden requirement, land sterilization and access tunnel impact each other.

2.4 Interaction between Parameters of a Group

When our attention is focused on one particular group, or a sub-system of the project, we will have interactions within the same group of parameters. The following matrix shows (Figure 5) how two parameters in underground excavations interact with each other (here we are examining the various parameters in a rock engineering system).

Although here we try to demonstrate the interaction between parameters of one group, it is evident the depth of caverns is directly related to overburden requirement from ammo safety. For discussion purposes, we add the overburden requirement as a primary parameter, which in turn requires determination of four additional interactions. The question marks are used to emphasize the need to think through how the overburden requirement in ammo safety will impact cavern design.

Cavern Dimensions *Size and shape*	Large caverns may be difficult in poor rock	?
Cavern size may be limited by depth	**Depth of Cavern** *Three depths possible*	?
?	?	**Overburden Requirement**

Figure 5. Interaction between parameters of a group

2.5 Resolution of the Interaction Matrix

In the preceding analysis, we have shown how the interaction matrix can be used to evaluate the system behavior. The amount of details in the interaction matrix determines its resolution. The matrix can have any number of parameters (minimum two). We can decide on how much details to include in the interaction matrix, depending on the purpose of the matrix. As shown in Figure 6, we can have the following three levels of resolution:

a. Low resolution - top level planning
b. Medium resolution intermediate management
c. High resolution - detailed planning and design

For a matrix with N primary parameters, there are a maximum of N(N-1) interactions. Theoretically, the resolution, or the number of primary parameters, N, can be changed to any level by combining or expanding parameters. However, for practical applications, it is important to limit the resolution to a small number of levels to avoid confusion and unnecessary work.

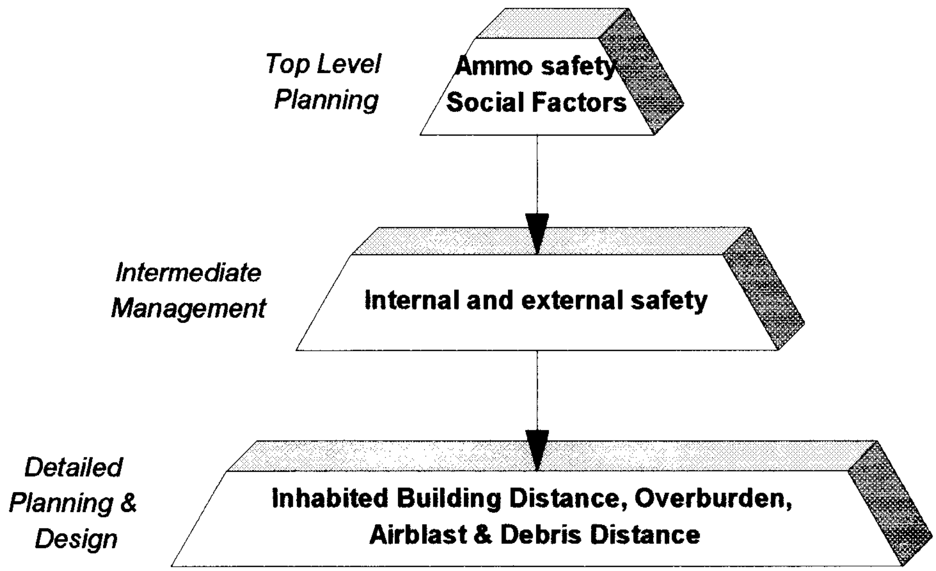

Figure 6. Three Possible Resolution Levels of the Interaction Matrix

3. EXAMPLE APPLICATIONS

In this section, we demonstrate the use of the interaction matrix by showing two examples from underground ammunition storage.

3.1 Systems Parameters

In order to construct any interaction matrix, we must first identify the parameters that will enter the matrix. It is not necessary to have all the parameters in the beginning, because the matrix can be updated (and changed) continually as is shown in Section 3. However, it is nevertheless desirable to have as complete a matrix as possible at each level of resolution.

Classification of the group parameters is another important step, as this will allow easy construction of interaction matrices of different resolution levels. For our example, we can identify the following systems parameters.

a. Objective Parameters:
   - User requirement
   - Minimization of land use
b. Solution Parameters
   - Cavern design/engineering

- Construction

c. Constraint Parameters
   - Ammo safety & social factors
   - Overall environment
   - Site conditions & rock mass quality

These group parameters, and the parameters under each group are shown in Table 1.

Note that the parameter New Technology appears both as a constraint parameter and a solution parameter. New technologies can be part of the technical solutions to engineering design, or it can become part of an existing safety codes.

Table 1. Systems Parameters for Underground Ammunition Storage

No.	Group Parameter	Parameters Under Each Group
1.	Overall Environment	General geology, climate, seismic risk, quarries, housing/existing structures (roads, utilities lines), highways, parks, etc.
2.	Site Conditions & Rock Mass Quality	Surface topography, soil cover, ground water, intact rock, jointing, faults, stress conditions, weathering
3.	User Requirement	Storage capacity, mode of storage, affordable loss, operations, transport, protection
4.	Ammo Safety & Social Factors	Sympathetic detonation, chamber separation, blast doors, airblast, ground shock, debris, glazing control , *New Technology*
5.	Cavern / Engineering Design	Site characterization, selection of site, siting of facility, dimensions, support, depth, number of caverns, expansion chamber, portal, access tunnels, shafts, *New Technology*
6.	Construction	Excavation method, timing, equipment, sequencing, ground vibration and noise

At this point, it is possible to construct the interaction matrix using the six groups as primary parameters (low resolution), or we may construct an interaction matrix for the parameters under each group (high resolution?), or a complete matrix with parameters from all six groups (definitely high resolution).

Again, it is important to point out that it is not necessary to have all the parameters in the beginning. In fact, the classification itself can also change, depending on the actual problem and the objective of the interaction matrix.

3.2 Examples

Once the parameters are identified, the interaction matrix can be constructed. Figure 7 show the interaction matrix using six group parameters as the main parameters. Based on our definitions in 2.5, this matrix can be classified as the top level planning matrix.

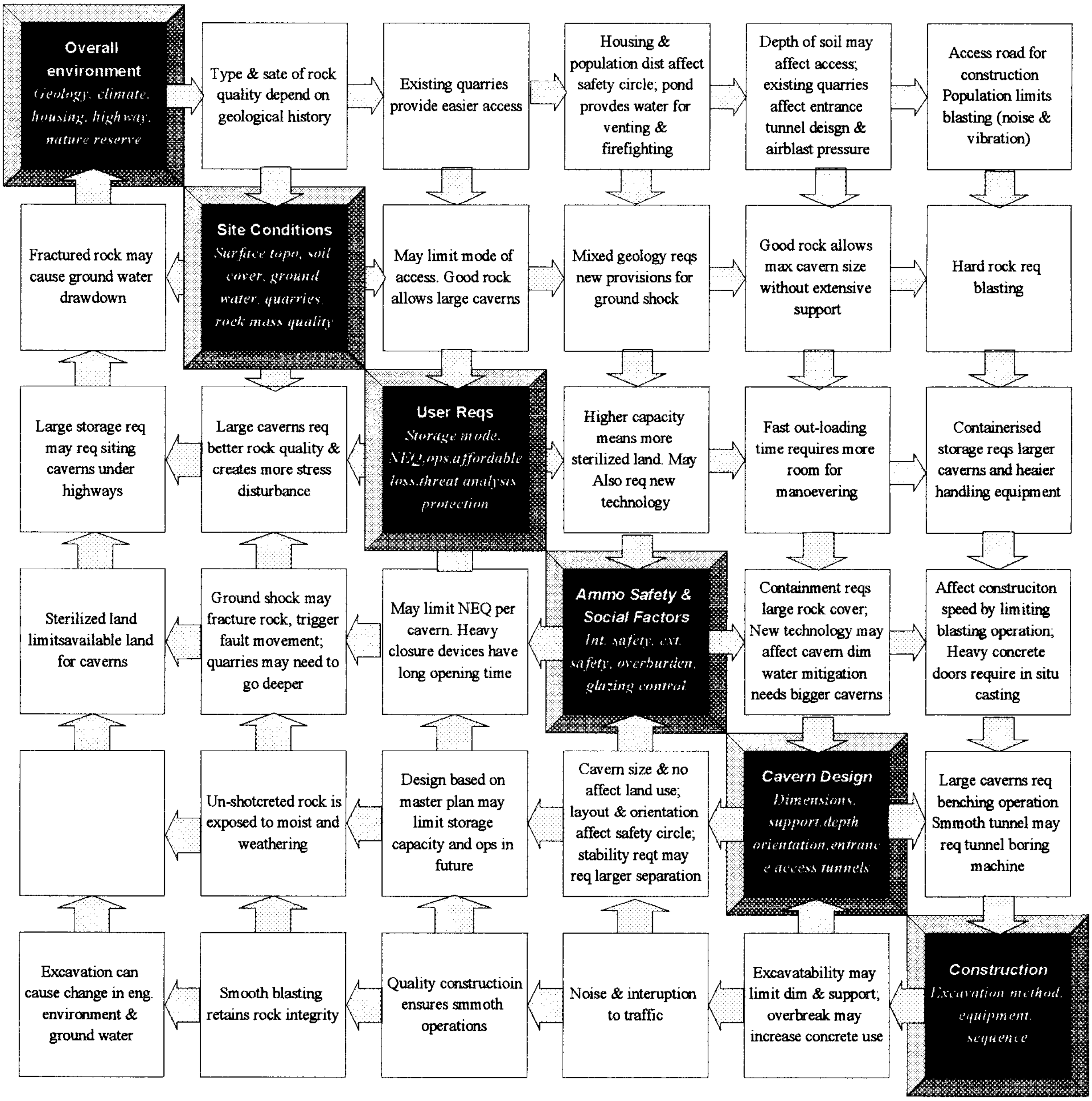

Figure 7. Interaction Matrix for Planning Underground Ammunition Storage Facility

The interaction matrix concept has been found to be very useful in helping us to develop the initial user requirements. Table 2 shows a list of parameters for user requirements and their possible effects on design. As can be seen, it is not an interaction matrix in the truest sense. Rather, it a collapsed form of the interaction matrix. This table was necessary for simplicity and clarify. A complete interaction matrix with all the detailed parameters would have been too complex and too cumbersome to manage at the initial stage. This example demonstrates another use of the interaction matrix. The table actually helped the user think about the possible effects of his requirements on the design.

4. CONCLUSIONS

Underground ammunition storage is a very complex subject. It involves very specialized areas in rock engineering, ammo safety, fortification design, and indeed technology development. The number of parameters is so large that only a systematic approach can ensure the most efficient and economic solution.

The interaction matrix has been found to be an effective tool for planning underground ammunition storage facilities. When properly used, it can assist us in evaluating the systems behavior of such a complex system. Once it is constructed, the effects of changing one parameter on the overall system behavior can be seen clearly and almost instantly, no matter how many parameters are involved. Nothing will be left to chance. It is also flexible and allows construction of matrices with different resolutions for varying purposes from top level planning to detailed planning and design. It can be updated or modified continually, and can be used to gather all relevant factors and interaction mechanisms in a coherent structure.

REFERENCES

[1] Hudson, A. John. 1992. *Rock Engineering Systems - Theory and Practice.* Ellis Horwood, New York. 185 p.

[2] Jenssen, Arnfinn, 1995. *Personal communications.*

Table 2. Use of Interaction Matrix Determination of User Requirements and Their Effects on Design

	Parameter	Design Parameters Affected
1.	**STORAGE CAPACITY** • Total Capacity • Mixture: HD1.1, HD1.2, etc. • Storage of HD 1.3? • Ammo Profile • Compatibility group	• No of caverns • Cavern dimension • Site layout & location • Fire-fighting facility
2.	**MODE OF STORAGE** • Pallets, stacking height, no of pallets per row, no of rows, NEQ per pallet, • Containers, Nos, stacking height • Mixed pallets and containers • Mixed ammo type in chambers	• Chamber dimensions • Branch tunnel • Access tunnel • Workshop area • Mechanical handing system • Blast door design
3.	**AFFORDABLE LOSS** • Resource Loss: percentage of total, maximum of one type • Functional Loss: percentage of total due to delay in access in an accident • Maximum time allowable for recovery and extraction of stock after an accident	• Facility layout: single- vs. grouped- vs. multiple- chamber • Number and length of access tunnels • Need for venting tunnels • Blast door design: no & size • Emergency power supply
4.	**OPERATIONS** • Issue, receipt, process of pallets/containers • Maximum retrieval time of entire complex • Minimum and desired rate of retrieval (i.e. no of pallets/hr, no of containers/hr) • Peace time operations: maintenance, offices, other facilities • Stuffing area, loading/pre-loading • Environmental control • Fire fighting	• Location / size of process area • Location of expansion chamber • Main tunnels • No of access tunnels and roads • Need for venting tunnels • Blast door design - opening & closing time • Slope of access tunnels • Vehicles • size of loading area.
5.	**TRANSPORT** • Transport equipment: prime-movers/flatbeds, etc. • Type: diesel, electric, etc. • Maximum load • Two-way traffic	• Ventilation requirement • Power supply • Chamber size • Door size • Dimension of access tunnels • Battery recharging room
6.	**PROTECTION** • Security monitoring • Threat analysis: sabotage, commando raid, air attack, biological & chemical attack • Level of protection: conventional weapons (e.g. SAP 1000 kg), gas, EMP, nuclear • Min separation between Entrances • Number of entrances • Environmental monitoring	• Portal design • Blast doors • Camouflage • Depth of chambers • Security systems • Hardening design • Centralized monitoring